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ORGANIC LIGHT EMITTING DIODES – INNOVATIVE LIGHT SOURCES

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ABSTRACT

This article is a review of the new light source – organic LEDs having prospects of application in general and special lighting systems. The article describes physical principles of operation of organic LEDs, their advantages and principal differences from conventional non-organic LEDs and other light sources. Also the article devoted to contemporary achievements and prospects of development of this field in the spheres of both general and museum lighting as well as other spheres where properties of organic LEDs as high-quality light sources may be extremely useful.

Keywords: organic light emitting diodes, OLED, light sources, colour rendering index, lighting

1. INTRODUCTION

Light emitting diodes (LED) have been being applied currently in lighting as a new light source gradually out-competing conventional light sources – different types of lamps. The organic LEDs (OLED) are a separate class of devices and the newest direction of development of solid state lighting (*SSL*). Though there are a limited number of commercial OLED panels in the market, lots of concepts and implemented projects illustrating capabilities of OLED are presented in open sources (Fig. 1).

They include lighting windows and ceilings including transparent ones, luminaires with different forms and configurations, luminaires based on flexible OLED panels. Currently, some qualitative characteristics of organic LEDs lag behind those of non-organic LEDs, for instance, luminous efficacy and service life, but the main constraining factor of their spread is their high cost. Nevertheless, gradual improvement of characteristics of OLED structures and start of their mass production, hence reduction of unit cost (*$*/lm) of these light sources alongside with their unique properties will lead to their wide spread.

2. PHYSICAL PRINCIPLES OF OPERATION AND DISTINCTIONS OF OLED

Both non-organic and organic LEDs belong to electroluminescent light sources which generate light inside the structure as a result of radiation recombination of carriers (electrons and holes) injected from anode and cathode respectively. But there are principal differences between physical principles of operations of white-light organic and non-organic LEDs. In non-organic LEDs, white light is generated as a result of mixture of original radiation of a crystal in the blue region of spectrum (electroluminescence) and fluorescence of phosphor mixture covering the crystal in the wide green-yellow-red region of spectrum (Fig. 2a).

The dimensions of the LED crystal rarely exceed 1×1 mm, and the power of LED is about 2 W or more. An example of a LED in a body with dimensions of 3.5×3.5 mm is shown in Fig. 2b. Low dimensions and such high specific capacity categorises non-organic LEDs as point light sources with high luminance and application of secondary optics (Fig. 2c) allows us to obtain almost any curve

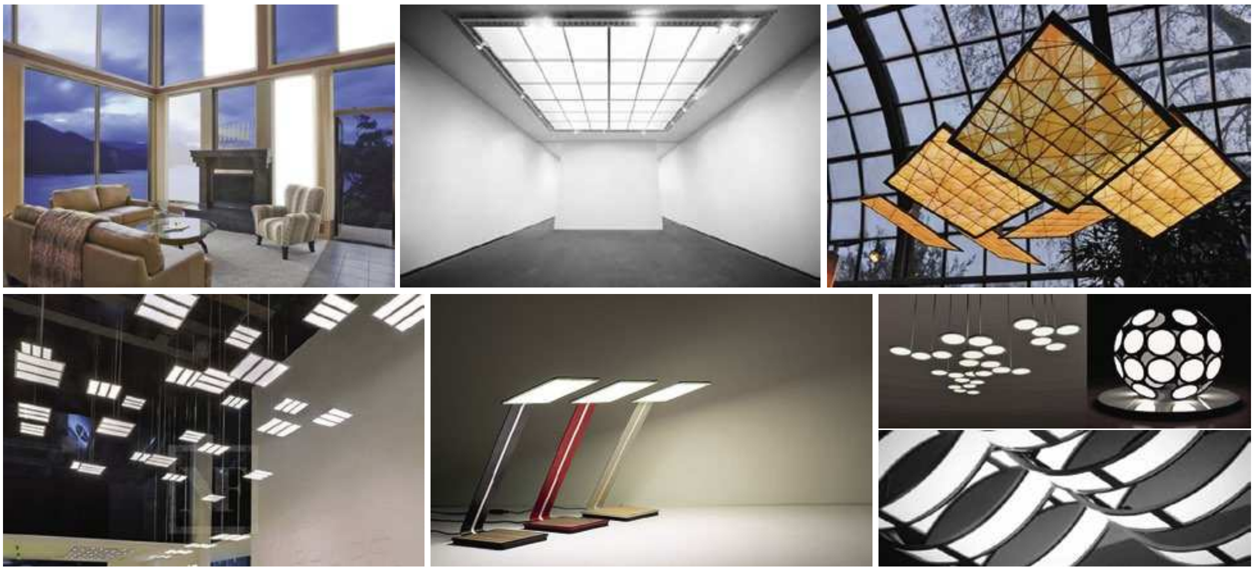


Fig. 1. Concepts and implemented projects based on OLED panels

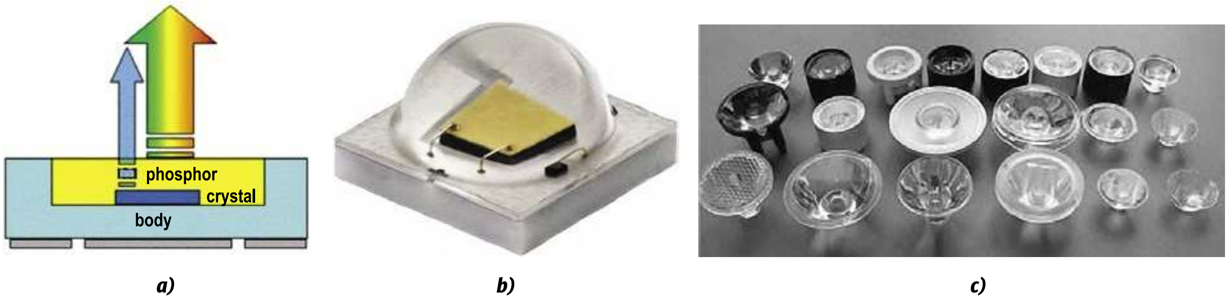


Fig. 2. Principal diagram of a white LED (a), example of a LED in a 3.5×3.5 mm body (b), secondary optics (c)

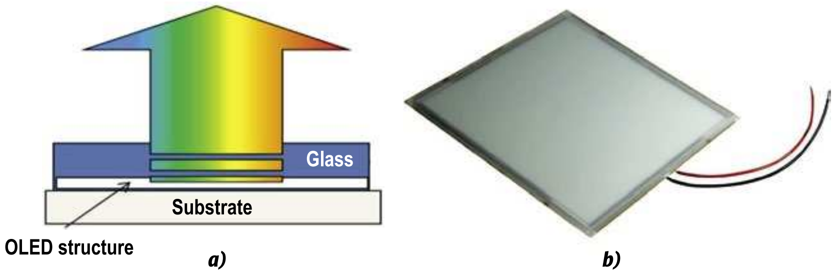


Fig. 3. Principal diagram of OLED (a), OLED panel by *LG Chemical* (b)

of luminous intensity. In order to obtain diffused light by luminaires based on non-organic LEDs, it is necessary to apply diffusers of different design and the body of the luminaire should provide efficient heat removing.

OLED is a thin-film multi-layer hetero-structure of organic semi-conductors mounted on a glass or non-transparent base (Fig. 3a). Radiation is uniformly distributed over the whole surface of the device and has almost ideal cosine curve of luminous intensity. For example, Fig. 3b shows an OLED panel by *LG Chemical* (Korea) with dimensions of 300×300 mm which is the distributed diffuse light source with thickness of just about 1 mm, which does not cause any glare effect. Heat is also distributed over the whole surface of the device and it does not require any additional constructive elements acting as a radiator. The most popular and technologically developed method of manufacturing of OLED is ultra-high vacuum thermal spraying method.

The structure of OLED contains up to 10 and more functional layers with thickness varying between 1 and 10 nm with total thickness of about

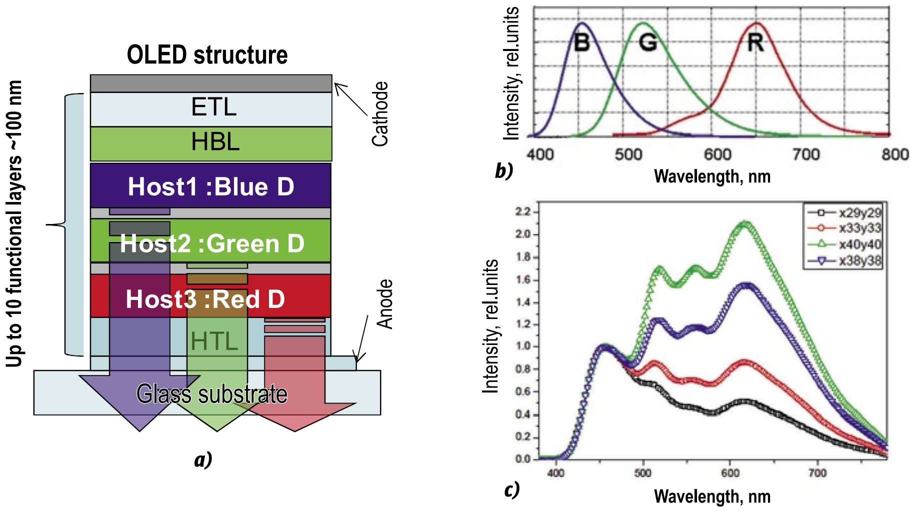


Fig. 4. Schematics of OLED structure (a), electroluminescence spectra of red, green and blue glow layers (b), electroluminescence spectra of white light OLED structure (c)

100 nm (Fig. 4a). The simplified structure of OLED contains a cathode and anode and an electronic transporting layer (*ETL*), a hole blocking layer (*HBL*), electroluminescent layers of matrix material and luminescent dopants with red, green and blue light (*Host* 1/2/3: *Red*/*Green*/*Blue D* respectively) and a hole transporting layer (*HTL*) located between them. Examples of electroluminescence spectra of red, green and blue light layers are shown in Fig. 4b. The half-breadth of spectral components is about 100 nm which is due to amorphous nature of organic semi-conductors, and the resulting spectrum of the white light structure with various colour coordinates, depending on the balance of components in the structure, is shown in Fig. 4c.

Therefore, OLED panels may have almost any colour or white light with different hues and corre-

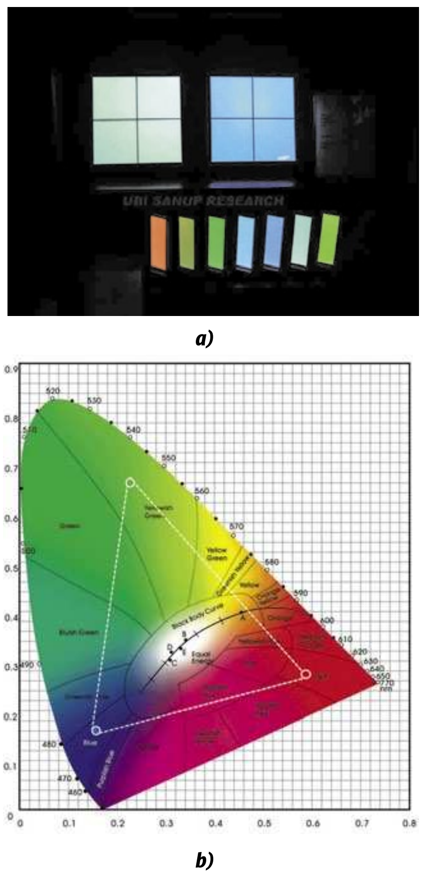


Fig. 5. Example of OLED panels with different hues of glow and shades of white (a) and colour space of CIE chromaticity coordinates *x*, *y*

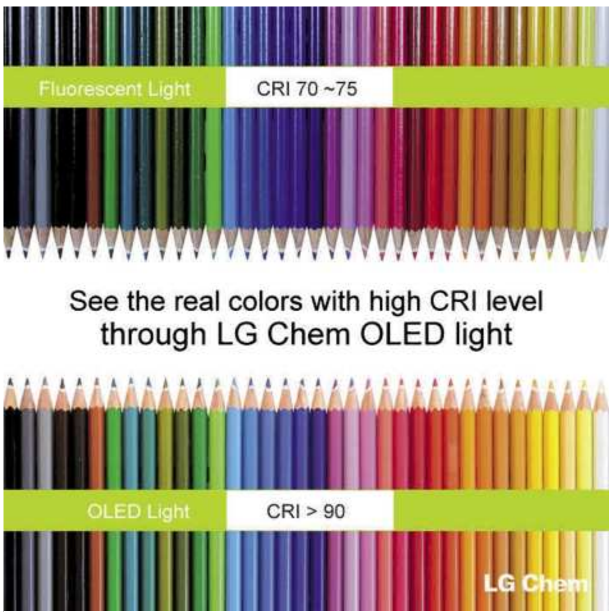


Fig. 6. Image from informational materials by *LG Chemical* as an example of colour rendering quality of OLED panels (above: lighting by means of a fluorescent lamp with colour rendering index of 70–75; below: OLED lighting with colour rendering index exceeding 90)

a) b) c)

Fig. 7. Application of diffused light sources: objective photo studio (a), art studio of Olga Gordon (b), *Ever BoutiqueMake-up* studio (New York) (c)

lated colour temperatures (Fig. 5a) with their chromaticity coordinates located within a triangle placed on the CIE colour space x, y chromaticity coordinates with its corners determined by spectra of red, green and blue colour of radiation.

3. QUANTITATIVE CHARACTERISTICS OF OLED AND THEIR CONTEMPORARY LEVEL

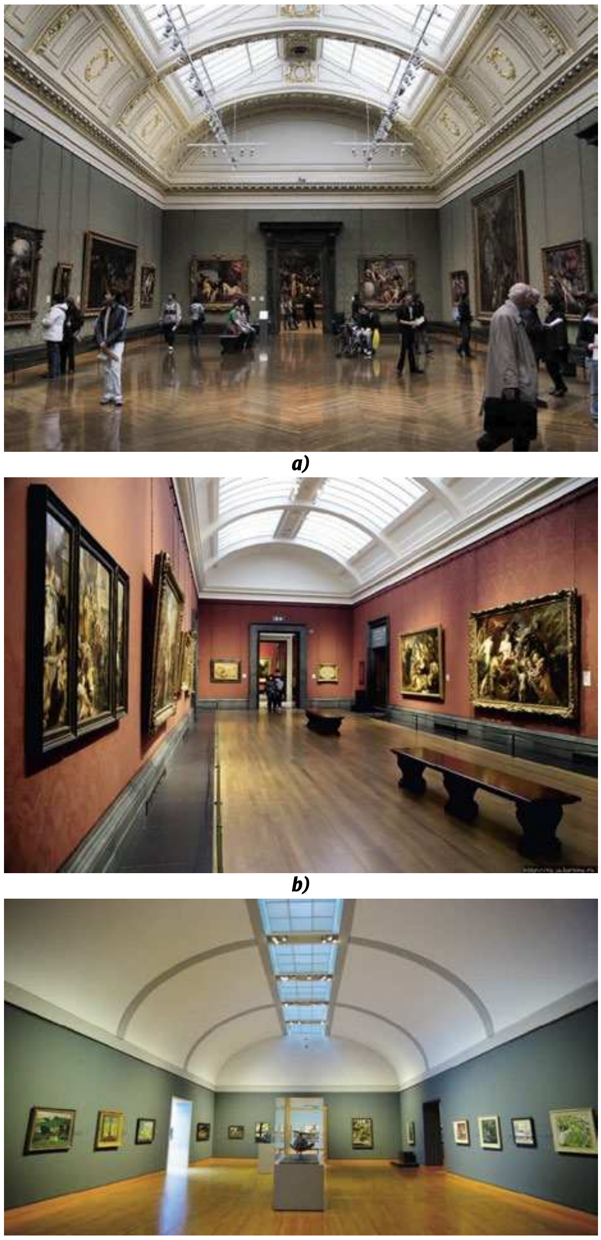
Displacement of points of major colours from the border of monochromatic colours inside the surface of spectral colours is determined by a rather large spectrum breadth of these components. In case of display applications, this feature may reduce colour gamut of a fully-coloured image and is compensated by application of *RGB* filters or more narrow-band irradiating materials and modes of their spraying.

In relation to lighting, the resulting spectra of white-light OLED structures have continuous spectral distribution without sharp peaks and crevasses and include almost the whole visible spectrum. Such spectral characteristic of OLED determines an extremely high quality of colour rendering of lighted objects irrespective of correlated colour temperature (Fig. 6).

As mentioned above, another important feature of OLEDs is their distributed nature with uniform diffuse glow all over the surface. This feature eliminates dazzling effect and lowers possibility of bright glares on smooth or reflective surfaces.

Such properties of OLED panels may be used in special systems of lighting, for instance, museum lighting and studio lighting where quality of colour rendering and lack of glares are extremely important (Fig. 7).

In museum lighting, the best result may be obtained in case of combination of point directed



a) b) c)

Fig. 8. Examples of combined museum lighting systems: National Gallery of Art in Washington, DC (a), The National Gallery of Great Britain (b), National Gallery of Canada (c)

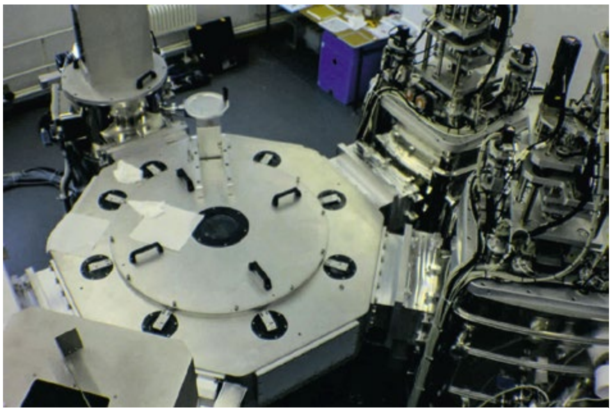


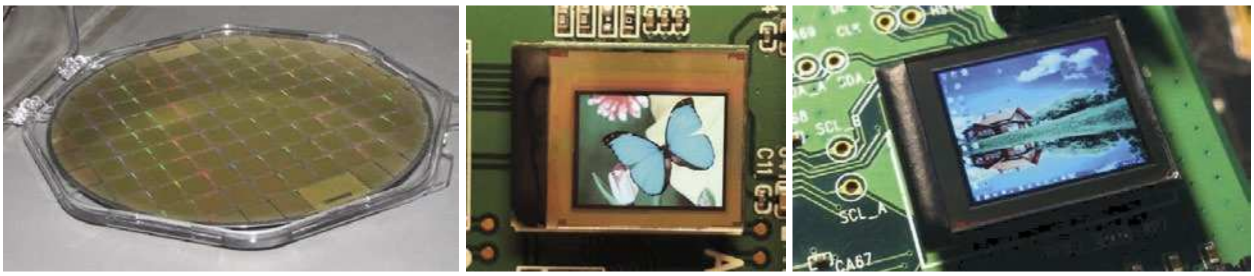
Fig.9. Vacuum cluster equipment for manufacturing of OLED devices (TsNIITsiklon, JSC/ TOPE, LLC)

lighting devices and distributed light sources. Natural lighting through glass roofs of buildings or its imitation with sources of artificial light hidden behind several layers of diffusing panels (Fig. 8) are traditionally used as a source of distributed light.

Luminous efficacy of organic LEDs is a little less than that of non-organic LEDs as it is illustrated in the Table.

The luminous efficacy of the best examples of commercial OLED panels is 65 lm/W which is significantly less than that of non-organic LEDs, for which luminous efficacy is about 180 lm/W and more. But luminous efficacy of multi-phosphor LEDs with high colour rendering indexes (~ 95) and correlated colour temperature of about 3000 K can be equal to just (80–100) lm/W. If it is necessary to create a light installation with uniform diffused glow, the losses on the diffuser system may be equal to more than 30 %, which makes the resulting luminous efficacy equal to that of OLED panels or even less. The luminous efficacy of laboratory samples of non-organic LEDs is already proximate to the theoretical maximum value and may exceed 250lm/W but with correlated colour temperature about 5000 K. According to information from reliable sources, the luminous efficacy of laboratory samples of OLED already exceeds 180 lm/W, which is equal to that of commercial non-organic LEDs. There is still a problem of relatively limited service life equal to 10,000 hours but it is being gradually solved by application of high-stability materials and enhancement of technology of encapculation of OLEDs which are extremely sensitive to atmospheric vapours of water and oxygen.

The main constraining factor of application of OLED panels is high cost of these devices, which is explained by non-availability of mass production of OLED panels in the world nowadays. At present, the world leading companies, such as *LG Chemical*, *Konica-Minolta*, *GE*, *Osram* and *Philips,* have been maintaining only small-batch production and their products are applied mainly in image-building pilot projects. Such situation is caused by necessity to develop a new type of expensive vacuum equipment adjusted for special aspects of production of OLED panels and allowing them to operate with bigger dimensions of substrates. Relatively rapid development of LED technology is caused by the fact that the technology of manufacturing of crystals is close to the technology of manufacturing of silicon microchips, where all technological equipment and processes have been worked out well. Nevertheless, the OLED technology has become widely applied for displays, gradually out-competing LCD screens. Nowadays, all flagship models of smartphones by leading manufacturers such as *Samsung* and *Apple* are equipped with OLED screens and full transition of the product line to this type of screens had been announced. There had been a similar situation with non-organic LEDs in the end of the 2000s when sharp increase of demand, increase of production volumes, and reduction of costs were connected with application of LEDs for backlighting of LCD screens. Therefore, if we suppose that the



a) b) c)

Fig. 10. Silicon plate with diameter of 200 mm with OLED micro panels (a), OLED micro display 02 PTs, 600×800 pixels, screen size 15 mm (b), mock-up specimen of an OLED micro display, 1,280×1,024 pixels, screen size 20 mm (c)

Table. Comparison of Development Levels of LED and OLED Technologies (2016)

Parameter	LED	OLED
Luminous efficacy, commercial products	180 lm/W (T_{cc} = 5,000 K, CRI = 70)	65 lm/W (T_{cc} = 4,000 K)
	100 lm/W (T_{cc} = 3,000 K, CRI = 95)	60 lm/W (T_{cc} = 3,000 K)
Luminous efficacy, laboratory samples	>250 lm/W (T_{cc} = 5,000 K)	>180 lm/W (T_{cc} – no data)
Service life	> 50,000 hours	10,000 hours
Cost	Low (mass production)	High (no mass production)
Process	Similar to *Si* technology	Special equipment

Note: T_{cc} is correlated colour temperature, CRI is CIE general colour rendering index

technology will be transferred to the lighting from display applications in a similar way OLED panels will be able to keep stable positions in the lighting equipment market in 10 years. U.S. Department of Energy and leading analysts forecast that the market of light sources and lighting devices, which takes a significant part of the global lighting engineering products with its estimated cost of €100 billion (by 2020), will be shared by LED and OLED devices in relation 60/40 by 2025. These suggestions are confirmed by increase of investments in OLED technology. For instance, *Konica-Minolta* (Japan) will invest ¥10 billion (*$*83 million) in an OLED panel plant with production capacity of 1 million 30×50 mm panels per year and forecasted revenue ¥50 billion already in 2020. *Merk* (Germany) invests €30 million in a plant for synthesis of organic materials for OLED with area of 2000 m^2, which will make it a very large facility in the field of high-purity materials production.

The only facility in the Russian Federation possessing a commercial-level OLED technology is JSC "TsNII "Tsiklon" (part of the Roselektronika Holding) and its subsidiary company OOO TOPE, which possess a high-vacuum cluster equipment for production of OLED devices as part of a closed automatic cycle (Fig. 9).

The facility started serial production of active matrix OLED micro-displays on 200 mm silicon bases with resolution of 800×600 pixels and screen size of 15 mm in monochrome white and full-coloured designs. The size of a pixel cell of this device containing three sub-pixels with major colours (blue, green and red) is 15×15 μm.

It is planned to finish development of OLED micro-displays with resolution of 1280×1024 pixels and screen size of 20 mm (Fig. 10) by 2019.

These products are used for ocular and binocular individual display devices, for instance, for virtual and augmented reality helmets (*VR/AR systems*) which have been gaining popularity recently. JSC "TsNII "Tsiklon" started developing OLED-based devices in the middle of 2000s and first laboratory samples of OLED panels on 40×60 mm bases were produced in 2007 (Fig. 11).

The luminous efficacy of white light laboratory samples was equal to about 30 lm/W at that time which is close to the global achievements of that period. Maximum luminance of OLED micro-displays of ocular devices is (50–100) cd/m^2 control

Fig. 11. Laboratory samples of OLED panels manufactured by TsNII Tsiklon, JSC

currents, moreover, the control current of the sub--pixels of the microdisplay matrix are only a few nanoamperes for an OLED structures with a similar level of luminous efficacy.

The lesser sub-pixel control currents are poorly controlled, especially in dark regions of gray gradations, so sufficiently larger values of luminous efficacy are not required for these devices. For projection-type information reproduction systems with OLED screen of a micro-display projected on a sufficiently larger area, a higher illuminance value may be required, therefore, a higher luminous efficacy will be needed for the purpose of energy saving. TsNII Tsiklon, JSC, keeps working for enhancement of parameters of OLED structures for micro-displays including luminous efficacy.

This experience may be used for development of OLED panels for general and special lighting including exhibition and museum lighting. The advantages of OLED panels may be critical for a number of other premises where more qualitative (from physiological point of view) light is required, for example, for premises intended for long presence of human without natural light (polar night in Arctic and Antarctic regions) and for pre-school institutions and prenatal centres where child's sight is not formed completely yet. For mass application in the field of household lighting where "quality" of light is also important, reduction of costs is necessary too what is possible only with mass production of OLED panels.

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graduated from Lomonosov Moscow State University, Department of Physics in 2002. At present, he is a Deputy Head of a Department, Deputy Chief Engineer for visualisation means of JSC "TsNII "Tsiklon". S.A. Stakhany is an author of a number of articles in the field of organic electronics including those in leading foreign journals, participant of Russian and foreign scientific conferences including the role of a guest speaker, member of the Svetotekhnika Scientific and Research Council. His Research Interests are OLED-based devices (indicators, active-matrix micro-displays, sensors, and field transistors), measurement of characteristics of OLED devices